ARO STIR GRANT FINAL REPORT DAAHO4-96-1-0230

HIGH STRAIN-RATE AND QUASI-STATIC DUCTILE FAILURE MECHANISMS IN POROUS MATERIALS

STATEMENT OF PROBLEM

This six month grant was used to investigate the interrelated physical mechanisms that can result in ductile material failure in rate-dependent porous crystalline materials subjected to finite inelastic deformations in aggregates subjected to strain-rates that span the quasi-static to the high strain-rate level. New multiple-slip crystalline slip constitutive relations and specialized computational schemes have been developed to characterize the effects of void growth and interaction and specimen necking on material failure have been for a single material cell, with a discrete cluster of four voids, where geometrical parameters have been varied to result in seven unique periodic and random void arrangements. The interrelated effects of void distribution and geometry, strain hardening, geometrical softening, localized plastic strains and slip-rates, and hydrostatic stresses on failure paths and ligament damage in face centered cubic (f.c.c.) crystalline materials have been studied. Results from this study are consistent with experimental observations that ductile failure can occur either due to void growth parallel to the stress axis, which results in void coalescence normal to the stress axis, or void interaction along bands, which are characterized by intense shear-strain localization and that intersect the free surface at regions of extensive specimen necking.

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13. ABSTRACT (Maximum 200 words)

An inelastic rate-dependent crystalline constitutive formulation and specialized computational schemes have been developed and used to obtain a detailed understanding of the interrelated physical mechanisms that can result in ductile material failure in rate-dependent porous crystalline materials subjected to finite inelastic deformations. The effects of void growth and interaction and specimen necking on material failure have been investigated for a single material cell, with a discrete cluster of four voids, where geometrical parameters have been varied to result in seven unique periodic and random void arrangements. The interrelated effects of void distribution and geometry, strain hardening, geometrical softening, localized plastic strains and slip-rates, and hydrostatic stresses on failure paths and ligament damage in face centered cubic (f.c.c.) crystalline materials have been studied. Results from this study are consistent with experimental observations that ductile failure can occur either due to void growth parallel to the stress axis, which results in void coalescence normal to the stress axis, or void interaction along bands, which are characterized by intense shear-strain localization and that intersect the free surface at regions of extensive specimen necking.

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SUMMARY OF THE MOST IMPORTANT RESULTS

The effects of void growth and interaction, and specimen necking, on the finite strain deformation and ductile failure of porous monocrystalline copper has been investigated for a cell with a cluster of four voids (Fig. 1). Within this single cell, geometrical parameters have been varied to result in seven unique periodic and random void arrangements.

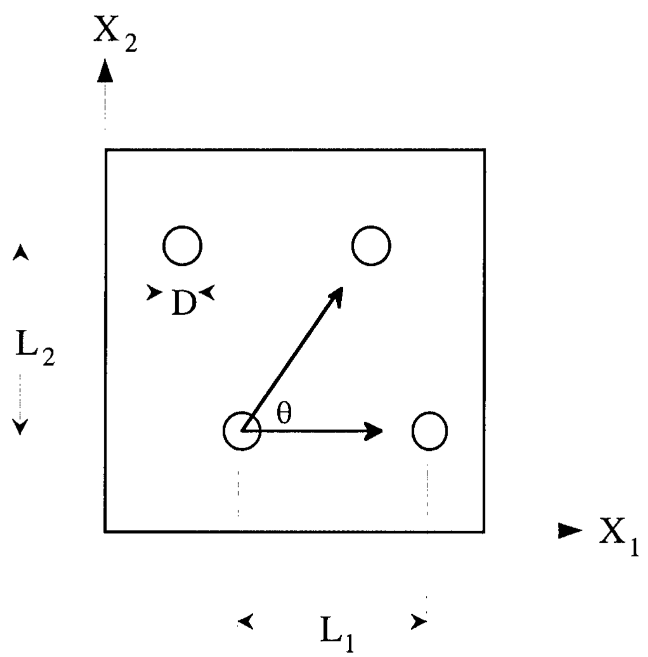


Figure 1 Four Void Cell Arrangement

In this investigation, it was shown that ductile failure can be characterized into two general categories: In the first category, if the void distribution is double or single periodic, and the initial horizontal spacing ratio is greater than or equal to 0.75, the lattice rotation, the slip-rates and the plastic accumulation activities are concentrated in the horizontal ligaments between the voids. There is also an accumulation of hydrostatic stresses, in this horizontal ligament region, that range from approximately 1.5 to 2 times the yield stress. These hydrostatic stresses result in void growth, due to volume changes,

parallel to the stress axis. This pattern of void growth, parallel to the stress axis, and the range of values for the hydrostatic stresses are consistent with experimental observations, for ductile fracture in polycrystalline pure copper and polycrystalline copper-aluminum alloys, that large values of the hydrostatic stresses indicate the onset of microvoid nucleation and growth. Critical spacing ratios, for specific arrangements, were also calculated to determine whether void coalescence would occur as shown in Table 1. Therefore, with the activity along the horizontal ligament, and with the horizontal spacing ratios approaching the critical spacing value of unity, void coalescence would most likely occur along this ligament normal to the stress axis at 5% nominal strain. It should also be noted that there was negligible deformation activity along the vertical ligaments.

In the second category, if the initial horizontal spacing ratio was less than 0.75, failure would either occur due to void coalescence along the horizontal ligaments, or due to intense slip activity along a shear-band that intersects the free surface at a region of extensive necking. The single periodic array with the 30° diagonal, the S30 model, has a horizontal spacing ratio, at 10% nominal strain, of 0.94 (Table 2). Therefore, void coalescence, normal to the stress axis, can result in material failure for this array. As the results have shown, there are high slip-rates, accumulated plastic strains, and hydrostatic stresses along the horizontal ligament. However, at comparable nominal strains, the accumulated local plastic strains in the S30 model are considerably lower than the corresponding values for the models in the first category. There is also a low rate of unloading of the nominal stress for this array and as stress contours have indicated, necking at the free surface is not as severe as compared with the other arrays in this category.

For the remaining periodic and random arrays, with initial spacing ratios of less than 0.75, there is intense slip and slip-rate activities, due to lattice rotation, along bands, linking upper and lower voids, that have evolved near the maximum shear-stress orientation of 45°. These bands intersect the free surface at a point of severe necking. This geometrical softening results in the global unloading of these void arrays. For these arrays, hydrostatic stresses are generally larger, in the ligament regions, than the

hydrostatic stresses in the region between the voids and the free surface at the necking region. Spacing ratios, between neighboring voids, were also calculated to determine if void coalescence would occur in any direction or orientation. As these results show (Table 2), the spacing ratios do not approach unity for any of the arrays. Therefore, failure in this case, will likely occur, as the results have shown, due to voids extending in shear towards the severe necking region. This will eventually result in shear strain localization along bands near the 45° maximum shear stress orientation. This is consistent with the experimental observations and results for the shear-strain localization (void-sheeting) of f.c.c. crystalline materials.

As the global stress response indicates, random arrays generally have lower ductility and a higher rate of unloading than the periodic arrays. Hence, these random arrays have the most severe necking. Also, shear strain localization occurred at lower values of nominal strain and these random arrays had larger slip rates than those values corresponding to the periodic arrays. The random array with the zigzag pattern of voids (R50 model) also has the lowest accumulated plastic strain of all the models tested.

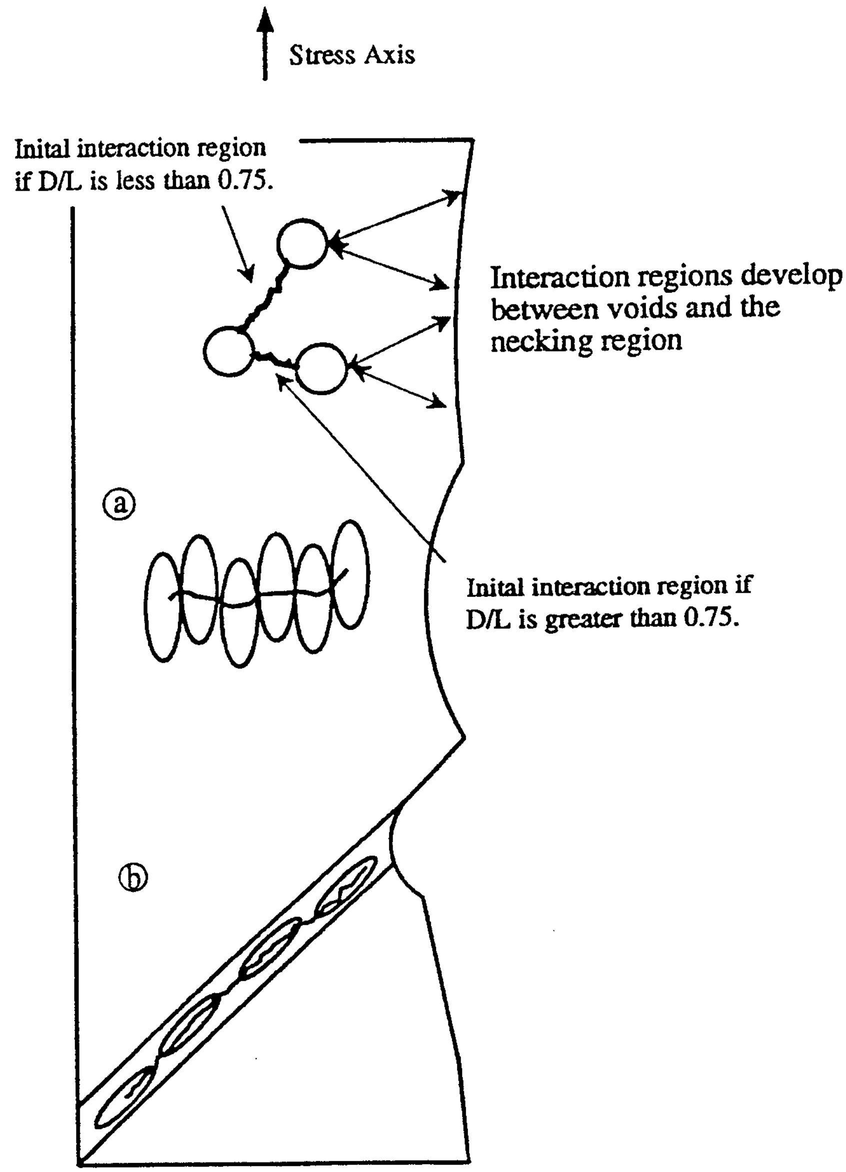
In summary, it has been shown that void spacing and distribution is directly related to whether the material fails by void growth and coalescence along a normal plane to the stress axis, or whether it occurs by shear strain localization along bands which form near the maximum shear-stress orientation and intersect the free surface at a region of severe necking (Fig. 2). These failure mechanisms could not have been characterized without the use of physically based constitutive formulations . It has also been shown that the use of symmetry conditions in unit cell calculations cannot accurately account for the interrelated mechanisms pertaining to fully represent deformed void geometries.

Table 1 Critical Spacing Ratios for Ductile Failure (Large Initial Spacing Ratio)

Void Array	Failure Strain	Spacing Ratio $\left(\frac{D}{L}\right)$	Failure Mode
D75	5%	0.97	Ductile Fracture
S60	5%	0.90	Ductile Fracture

Table 2 Critical Spacing Ratios for Ductile Failure (Small Initial Spacing Ratio)

Void Array	Failure Strain	Spacing Ratio $\left(\frac{D}{L}\right)$	Failure Mode
D25	20%	0.63	Void Sheeting
D25R	20%	0.69	Void Sheeting
S30	10%	0.97	Ductile Fracture
R25	5%	0.52	Void Sheeting
R50	10%	0.61	Void Sheeting



Stress Axis
Inital interaction region
if D/L is less than 0.75.
Interaction regions develop
between voids and the
necking region
ⓐ
Inital interaction region if
D/L is greater than 0.75.
ⓑ

Fig. 2

MANUSCRIPTS

V.C. Orsini and M.A. Zikry (1999), Void Growth and Interaction in Crystalline Materials, International Journal of Plasticity, in press.

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